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CONCENTRATIONS AND EMISSIONS IN A CALL CENTER**

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ABSTRACT

A study of the relationship between outside air ventilation rate and concentrations of VOCs generated indoors was conducted in a call center. Ventilation rates were manipulated in the building's four air handling units (AHUs). Concentrations of VOCs in the AHU returns were measured on 7 days during a 13-week period. Indoor minus outdoor concentrations and emission factors were calculated. The emission factor data was subjected to principal component analysis to identify groups of co-varying compounds based on source type. One vector represented emissions of solvents from cleaning products. Another vector identified occupant sources. Direct relationships between ventilation rate and concentrations were not observed for most of the abundant VOCs. This result emphasizes the importance of source control measures for limiting VOC concentrations in buildings.

INDEX TERMS

Ventilation, VOCs, Formaldehyde, Emission factors, Office buildings

INTRODUCTION

The importance of adequate ventilation in office buildings is supported by a number of studies that have investigated the association of ventilation rates with human responses as reviewed by Seppanen et al. (1999). Many of the included studies found that ventilation rates below 10 L s^{-1} per person were associated with one or more adverse health or perceived air quality outcomes. Ventilation rate increases above this rate were found in some studies to decrease symptom prevalence or to improve perceptions. These improvements were presumably due to reductions in concentrations of indoor contaminants, such as volatile organic compounds (VOCs). Mass balance considerations directly relate ventilation and concentrations of contaminants generated indoors. However, in practice the relationship is complicated by a number of potential factors affecting ventilation rates, air mixing, source strengths and removal mechanisms (ibid.). Ventilation additionally influences chemical reactions among indoor contaminants (Weschler and Shields, 2000). Thus, the effectiveness of ventilation for controlling indoor VOC concentrations may vary widely within and among buildings.

This study was conducted in support of an investigation of ventilation rate and worker productivity in a call center (Fisk et al., 2002). The primary objective was to determine how concentrations of VOCs generated indoors were affected by manipulated ventilation changes.

METHODS

The study was conducted in a health maintenance organization call center located in the San Francisco Bay Area. The building, constructed in 1998, had two floors, a total floor area of $4,600 \text{ m}^2$, and a worker density of ~ 6.3 persons per 100 m^2 (~ 290 persons). The building was ventilated and conditioned by four air handling units (AHUs 1-1, 2-1, 2-2 and 2-3) located on the rooftop. Each AHU served a defined interior zone ($840\text{--}1,460 \text{ m}^2$), although there likely was considerable air mixing among zones. AHU 2-2 served the entryway, lounge, and offices for management staff and meetings. Advice nurses and support staff occupied the other zones.

Each AHU had an economizer control system. Equipment was added to enable manipulation and measurement of outside air ventilation rates as described elsewhere (ibid.). For the three AHUs serving advice nurses, three fixed damper positions were selected to provide periods of low, medium, and high ventilation rates. The damper positions for the low period were fixed to provide near the code-minimum outside air supply rate of $76 \text{ L s}^{-1}/100 \text{ m}^2$. The damper positions for medium and high periods were selected to provide about 2- and 4-times the code minimum. The dampers in AHU 2-2 were fixed in one position. Using these methods, periods of ventilation were scheduled over 13 weeks (July 28 through October 24, 2000) in one of four modes: low, medium, high, and economizer mode (ibid.). CO_2 concentrations were measured on a 7-min cycle in all supply and return air systems and outside air.

Sampling for volatile organic compounds (VOCs) and aldehydes was conducted on weeks 2, 3, 6-8, 11 and 13. Air samples were collected from the return air ducts of the four AHUs and outside air on Tuesdays. Sampling began at 9:00 and ended at 15:00 to include the period of maximum occupancy. VOC samples were collected on sorbent tubes and analyzed for 49 compounds by thermal desorption GC/MS. Formaldehyde and acetaldehyde samples were collected on treated cartridges and analyzed by HPLC. The methods are described elsewhere (Hodgson et al., 2000). There were 6 field blanks for VOCs and aldehydes and 12 VOC sample pairs. Concentrations of individual VOCs and aldehydes (ppb; 25°C , 1 torr) and CO_2 (ppm) were determined for each zone and day of sampling. Emission factors ($\mu\text{g m}^{-2} \text{ h}^{-1}$) were calculated by simple mass balance using the concentration data, the outside airflow rates in each AHU and the floor areas of the zones. Seven of the 28 samples were excluded from this analysis because sampling started shortly after an airflow rate was changed and the zone was not near steady-state conditions during a sufficiently long portion of the interval. The emission factors of the 10 predominant compounds plus CO_2 in the 21 samples collected at steady state were subjected to principal component (PC) analysis to identify groups of co-varying compounds based on common source types. The software was StatView for Windows (Ver. 5.0.1, SAS Institute Inc.). The varimax rotation method was employed.

RESULTS AND DISCUSSION

The normalized airflow rates ($\text{L s}^{-1}/100 \text{ m}^2$) are presented in Figure 1. By design, AHU 2-2 flow rates remained relatively constant ($<25\%$ variation). There was an approximate 5-, 7- and 3-fold variation over the 7 days between the low and high rates in AHUs 1-1, 2-1 and 2-3, respectively. The building average flow rates ranged between 118 and $285 \text{ L s}^{-1}/100 \text{ m}^2$ over the 7 days. These are equivalent to 1.5-3.8 times the code-minimum outside air supply rate.

Since the primary focus was on contamination sources associated with the building and occupants, indoor minus outdoor (In-Out) VOC and CO_2 concentrations were calculated. This eliminated outdoor motor vehicle contamination from consideration. Of the 51 analytes, which included abundant, toxic and odorous compounds, only 10 had median In-Out concentrations for the 28 samples in excess of 0.5 ppb (Table 1). With the exception of formaldehyde and acetaldehyde, the In-Out median values for these 10 exceeded their median outdoor concentrations by a factor of two or more. The concentrations of the predominant VOCs were generally consistent with central tendencies and maximum values reported in cross-sectional surveys of U.S. office buildings (Daisey et al., 1994; Girman et al., 1999). There were at least 6-fold variations in individual VOC concentrations with space and time over the 7 days. Sampling in week 7 was preceded by four days at the medium ventilation rate in all zones. At this condition, the In-Out concentrations of CO_2 and all VOCs except acetaldehyde and d-limonene varied by less than a factor of three among all four zones.

Table 1. Concentrations and emission factors of most abundant VOCs and CO_2 .

Compound	Concentration (ppb)			Precision (%)	Emission Factor ^a ($\mu\text{g m}^{-2} \text{h}^{-1}$)	
	Outdoor Median	In-Out Median	In-Out Range		Median	Range
Ethanol	9.0	26	7.0-112	12	380	153-780
Isopropanol	9.8	29	8.7-240	5	550	94-2,400
2-Butoxyethanol	1.2	2.6	0.7-17.8	4	62	14.7-990
Acetone	4.9	9.8	2.1-39	46	190	29-410
Formaldehyde	4.4	6.2	3.1-20	<15	40	20-174
Acetaldehyde	1.7	1.5	<0.1-3.2	<15	16.2	6.2-30
Hexanal	0.3	0.9	0.3-1.9	15	21	13.0-48
Isoprene	0.1	0.6	<0.1-2.6	22	10.9	5.5-28
d-Limonene	<0.1	0.8	0.2-4.9	4	27	17.0-79
D5 Siloxane ^b	<0.1	2.3	1.0-7.4	6	230	114-300
ΔCO_2 (ppm, $\text{mg m}^{-2} \text{h}^{-1}$)		210	122-510	--	56	35-80

^aSummary for 21 samples collected near steady-state conditions. ^bD5 = defined in text.

The first four rotated principal components (PCs) of the analysis of VOC and CO_2 emission factors accounted for 79% of the total variance (Table 2). Tentative source identifications were made based on the most highly correlated compounds for each vector and information on likely sources. PC1 with high loadings of acetone, isopropanol and 2-butoxyethanol most likely represents the emissions of solvents from cleaning products (Zhu et al., 2001). Formaldehyde also has a high loading on PC1. PC3 with high loadings of

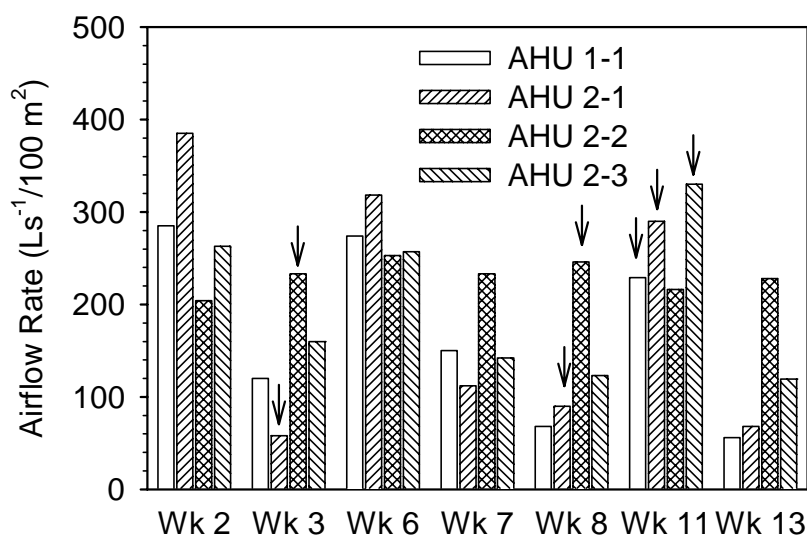


Figure 1. Normalized airflow rates in four AHUs on 7 sampling days. Arrows indicate non-steady state conditions.

decamethylcyclotrisiloxane (D5) and CO_2 presumably represents occupant sources as CO_2 is from breath and D5 is used in personal deodorants and has been associated with occupancy (Shields et al., 1996). Formaldehyde also is correlated with PC3. It is unclear why isoprene is not correlated with this vector, as isoprene is a predominant VOC in breath (Fenske and Paulson, 1999), and isoprene concentrations were generally consistent with an occupant source. d-Limonene, which is highly loaded on PC4, is used as an air freshener and as an

odorant and active ingredient in cleaning products (Zhu et al., 2001). Ethanol and formaldehyde are negatively correlated with this vector. The source of PC2 could not be deduced. Acetaldehyde and hexanal are both emitted by composite wood products (Hodgson et al., In press). However, wood products typically emit hexanal at much higher rates than acetaldehyde rather than the similar rates seen here. Also, wood products are sources of formaldehyde, which is negatively correlated with this vector. Ethanol and isoprene are both emitted in breath, but the ratio of their emission rates does not match this source (Fenske and Paulson, 1999).

The results of the PC analysis suggest that indoor air chemistry related to ozone may have impacted the concentrations of some VOCs. On the 7 sampling days, maximum 8-h values of outdoor ozone, obtained from a regional monitoring station, ranged between 25 and 42 ppb. Indoor ozone levels vary with ventilation rate and are frequently 20-70% of outdoor levels due to surface removal and homogeneous reactions with other chemicals in air (Weschler, 2000). At 50 ppb, the half lives of isoprene and d-limonene when reacted with ozone are 13 and 0.75 h, respectively (ibid.). Formaldehyde is a major product of these reactions. This is one explanation for the negative correlation of formaldehyde with d-limonene and isoprene in PC4. It is also a possible explanation for the weak relationship of isoprene with CO₂ in PC3.

Table 2. Loadings of the first four rotated principal components for an analysis of emission factors of abundant VOCs and CO₂.

Compound	PC1	PC2	PC3	PC4
Ethanol	0.21	0.72	0.26	-0.25
Isopropanol	0.92	0.076	0.031	0.117
2-Butoxyethanol	0.90	-0.169	0.25	-0.078
Acetone	0.88	0.32	0.012	0.163
Formaldehyde	0.56	-0.40	0.62	-0.27
Acetaldehyde	-0.051	0.84	-0.177	-0.027
Hexanal	-0.007	0.84	0.147	0.100
Isoprene	0.081	0.54	0.064	0.43
d-Limonene	0.100	-0.073	0.24	0.88
D5 Siloxane	-0.056	0.081	0.84	0.24
CO ₂ (ppm)	0.28	0.26	0.81	0.143
Variance (%)	32	23	14	10
Cum. Var. (%)	32	55	69	79

The In-Out concentrations of six VOCs variously identified with the range of source categories are plotted in Figure 2 versus normalized airflow rate. Only steady state data is included. The concentrations of isopropanol and 2-butoxyethanol, two compounds with likely cleaning product sources, showed little relationship with ventilation; although, the two highest isopropanol values occurred at the

lowest airflow rates. Formaldehyde concentrations also were not apparently associated with ventilation as the concentrations in the zones served by AHUs 2-2 and 2-3 were nearly identical and constant throughout the study. Formaldehyde concentrations in the zones served by AHUs 1-1 and 2-1 were mostly higher possibly indicating a localized source; but, they were not associated with ventilation. Concentrations of acetaldehyde, hexanal, ethanol and isoprene (last two not shown) in zones served by AHUs 1-1, 2-1 and 2-3 exhibited trends of higher concentrations at lower flow rates to varying degrees. The concentrations of d-limonene were not strongly associated with ventilation.

Understanding sources and evaluating the efficacy of ventilation for controlling the concentrations of VOCs emitted by these sources is difficult, particularly for large buildings. Direct relationships between VOC concentrations and ventilation may be obscured by a

number of factors in addition to homogeneous air chemistry. There may be overriding temporal and spatial variations in source strengths. For example, concentrations of compounds that are solvent constituents of products used intermittently or sporadically and occasionally in large quantity would not be expected to exhibit strong inverse relationships with ventilation. This was apparently the case for acetone, isopropanol and 2-butoxyethanol. Ventilation and airflow rates may influence VOC emissions from wet products applied to surfaces and from building materials, furnishings and other solid sources. The sorption of VOCs onto surfaces in the building and their later release when bulk air concentrations decline also directly links VOC emissions with ventilation. For some common VOC/material combinations, this effect is predicted to be relatively large (Zhao et al., In press). These processes, plus imperfect air mixing and air chemistry, reduce the effectiveness of ventilation for controlling VOC sources.

CONCLUSIONS

Differences in the concentrations of most of the abundant VOCs in the building on 7 days of sampling could not be directly predicted by differences in ventilation rates on those days. Temporal and spatial variations in cleaning products likely obscured the relationship between concentration and ventilation for solvents. For other compounds, it is likely that effective emission rates increased with ventilation due to their re-emission from sinks. Homogeneous chemistry also may have altered the relationship between ventilation and concentrations of some reactive and product compounds. These results emphasize the importance of source control for limiting the concentrations of VOCs in buildings. Control procedures include use of low emitting materials to finish and furnish interiors, use of low-emitting cleaning products, and avoidance of products containing highly reactive chemicals.

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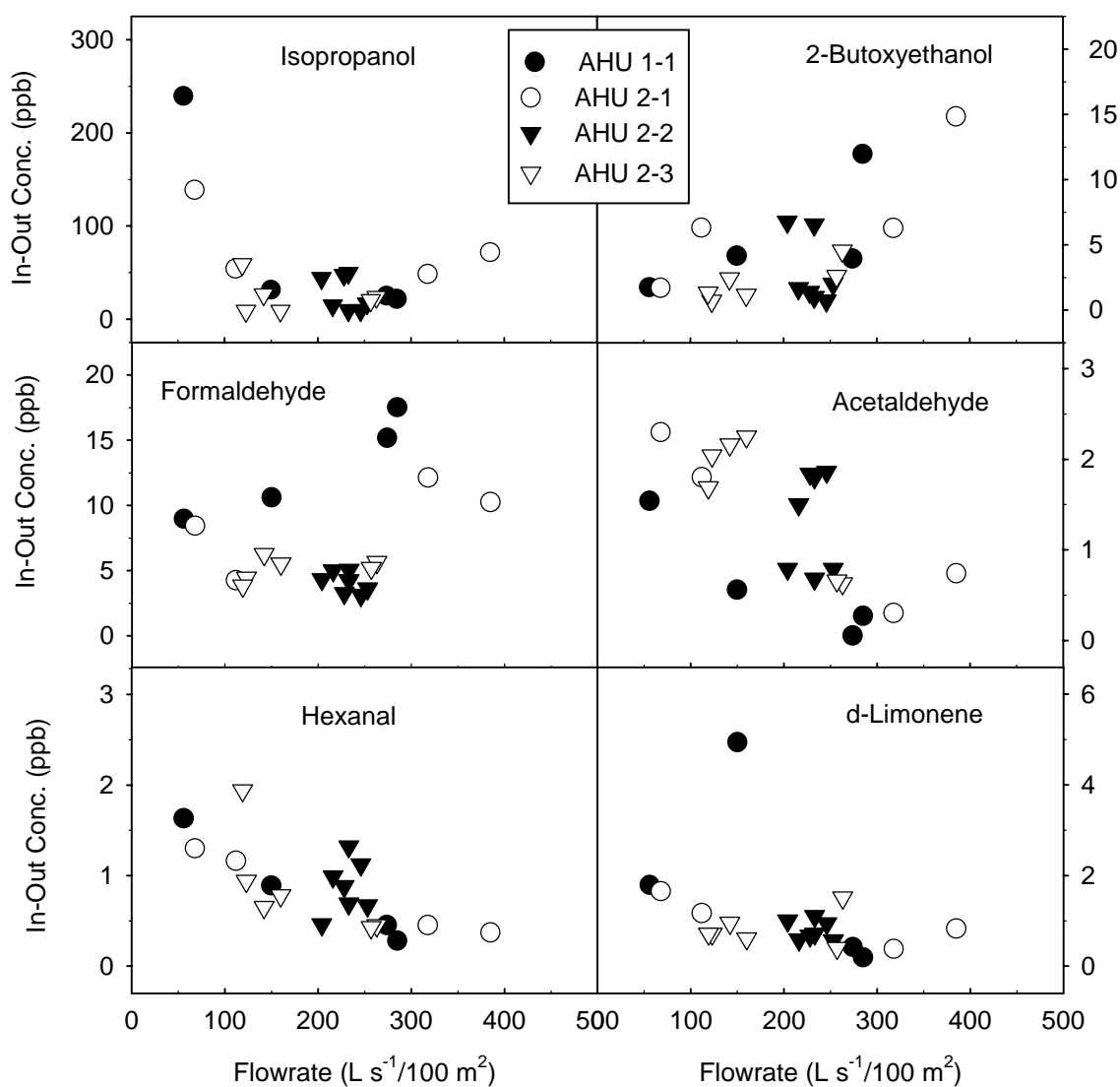


Figure 2. Indoor minus outdoor VOC concentrations in four AHUs on 7 sampling days versus normalized AHU airflow rates.